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Subject: **Final Report for 1-3 Composites Study**

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Summary

The first report focused primarily on a quantitative comparison between solid ceramic, conventional 1-3 material, and an unfilled bar matrix in the context of transducers employing mass-loading ("capped") to reduce the resonance frequency. Such structures are typical of low- to moderate-frequency applications. The attributes of capped and uncapped 1-3 composite are markedly different, however. When uncapped, the fill material is an active part of the radiating face and the resonance is determined almost entirely by the thickness of the 1-3 material. From a performance standpoint, the filler in a capped design is primarily a liability. The filler serves the purpose of holding the ceramic matrix together during production but, once assembled, the filler degrades the performance.

This report is more qualitative. It represents a distillation of conversations with researchers who have experience with 1-3 composites in both low- and high-frequency applications. However, it is not solely a repetition of opinions; the views of others have been used to identify important practical issues. The intent here is to summarize these issues and indicate the strengths and weaknesses of 1-3 material in light of these issues.

Several of the more important conclusions in no particular order are:

- Transducer configuration is critically important in determining the applicability of 1-3 composite. The material is often used to advantage in thickness self-resonance designs (as it would typically for frequencies above 100 kHz). At lower frequencies, when the material is mass-loaded, the 1-3 composite has less of an advantage over solid ceramic.
- In a transducer in which the active material is sandwiched between mass elements (a tonpilz being one such configuration), the filler in a 1-3 composite degrades *performance* with respect to an unfilled array of piezoelectric rods. (This is discussed

in detail in the first report.) The filler may be advantageous in the *production* of such transducers, however, as a temporary binder for the rods.

- Self-heating is not the only obstacle to successful use of PZT5H in high-power composites. At high drive levels, the dielectric loss contributes substantially to the reduction in overall efficiency. Furthermore, the "high" drive levels for PZT5H are far below acceptable high drive levels for PZT4. These issues are not resolved by increasing thermal conductivity of the filler. (Overheating the filler and the potential for thermal runaway may be addressed by modifying the thermal conductivity of the filler.)
- If PZT5H must be considered seriously for high-power operation, then its performance under unipolar drive should be examined. Since a large part of the dielectric loss can be attributed to domain reorientation in the "wrong" direction from an electric field opposite to the average polarization direction, unipolar drive *might* reduce the dielectric loss and might increase the useable maximum electric field to acceptable levels.
- The two principal problems associated with injection-molded 1-3 composites are the considerably greater variability in properties across a production run compared to dice-and-fill and the bias toward the easier-to-sinter PZT5H.
- Results must be reported completely in order to be useful for the transducer design community. Low-drive measurements are not representative of high-drive results. A performance quantity (efficiency or TVR, for example) must be measured at the intended drive levels and over the entire relevant frequency range.

Importance of Configuration

In considering the advantages and disadvantages of composites, it is critically important to consider the transducer configuration. A supposed advantage in one situation can be neutral or a disadvantage in another. In fact, many arguments regarding the suitability of 1-3 material can be resolved by focusing on the integrated system that comprises the drive electronics, piezoelectric material, transducer structure, and performance specifications. Although there are many possible transducer configurations, here, two main categories will be used to illustrate the problem:

- Direct radiating 1-3 material used in thickness resonance mode ("uncapped")
- 1-3 material used as active layer in mass-loaded transducer ("capped")

For example, many high-frequency applications (applications of the material at thickness-mode resonance without mass loading – above 100 kHz, for example) use the 1-3 material in thickness resonance and depend on motion of the filler to mitigate the lost active area since they operate without stiff caps (but often with matching layers). In these applications, the 1-3 material can often be used to advantage. In contrast, if the material is used as the active layer in a front- and back-loaded transducer (like a tonpilz), then dicing can still improve the effective coupling factor but the filler limits that improvement by transferring the motion of a face plate to the ceramic elements in the wrong direction. In these applications, an unfilled matrix of ceramic elements outperforms a filled matrix. Of course, the matrix may serve a practical function in production – holding the ceramic elements together until bonded to head and tail structures.

On one hand, then, are those applications in which the material is used in thickness resonance and is uncapped (except for compliant matching layers). These are higher frequency applications since there are practical limits on the thickness of a 1-3 layer and, for thickness resonant operation, lower frequencies require thicker material. One-inch layers have been fabricated but this may be near the practical limit of current fabrication. Multiple layers can be used but the ceramic elements must be aligned from layer to layer and this complicates production. These applications are typically above 50 kHz.

On the other hand are those applications in which the material is used primarily as compliance in a mass-compliance resonance. Here, the material is mass loaded (hence capped). In such configurations, may of the advantages of 1-3 material are not realized. In fact, an advantage in thickness-resonance mode – like the suppression of lateral resonances compared to solid ceramic – can cause trouble in the compliance mode where the lateral resonances may be in the band of interest. These applications are typically well below 50 kHz and are often driven to maximum power.

The short story is that 1-3 material seems to be well suited for a number of applications in high-frequency, thickness-resonant transducers and that 1-3 material has little advantage and some penalty for applications in which it is mass loaded for low- to moderate-frequency.

The discussion that follows is organized by issue. This is not a complete discussion of all relevant issues regarding transducer design. Rather, several key issues have been selected that are especially relevant to 1-3 material and, in many cases, address the areas in which 1-3 is normally claimed to have some advantage over solid ceramic.

These issues are

- Injection Molding vs. Dice-and-Fill
- Lateral (Spurious) Modes
- Self Heating
- Bandwidth
- Stress and Failure
- Unipolar Drive

Each issue will be presented with a short summary list followed by a discussion.

Injection Molding vs. Dice-and-Fill

- Low production cost for injection molding
- Poor uniformity in material produced by injection molding
- PZT5H easier to sinter in injection molding process
- PZT5H has larger *d* coefficients than PZT4/8
- PZT5H has lower electric field tolerance with respect to depoling
- PZT5H has much higher dielectric loss

One of the advertised advantages of injection-molded 1-3 composite is low production cost; however, a principal disadvantage of injection-molded 1-3 material is the lack of uniformity in properties. Ordinary piezoceramic material is cast and fired under pressure expressly to promote uniformity but, to date, a practical process for cast/fire under pressure has not been demonstrated for injection molding or extrusion processes. Presently, if a number of elements with matched properties are required, an excess of material is produced and parts are tested and sorted to obtain the required matching. For the limited variability required by typical array applications, dice-and-fill can be competitive in cost because of higher yield.

Another aspect of molded 1-3 is that, in the context of the molding process, PZT5H is easier to sinter than the hard ceramics. Consequently, there is emphasis on using the softer material for injection-molded composites. This limitation is often cited as an advantage since the piezoelectric *d* coefficient values are about twice those of the harder materials. All other things being equal, this would make PZT5H better material for transmitting transducers. However, the coercive field is much lower in PZT5H than in 4 or 8 so the maximum electric field for driving without depoling is much lower. This in itself erases the advantage of the larger *d* coefficient. In principle, this could be overcome by unipolar drive (a DC offset added to the AC drive signal so that the field never reverses in the material). Certainly, if the application is limited to low drive levels and the application is voltage limited, then the larger *d* of PZT5H is advantageous.

The attribute that cannot be avoided is the much higher loss tangent under high drive levels in PZT5H (again, compared to PZT4 or PZT8). A relatively high efficiency at low drive level degrades substantially at high drive level (to a much greater degree than with the harder ceramics). Furthermore, the loss tangent grows with temperature so the possibility of thermal runaway (in PZT5H especially) must be considered.

One aspect of injection molding compared to dice-and-fill that has not been explored is susceptibility to mechanical failure. If the 1-3 composite is not operated under prestress, then the operating stress must be kept low enough to avoid tension failure. The tensile strength appropriate for ceramic in bulk can be highly optimistic when applied to smaller structures with uncertain surface finish. The surface finish in the vicinity of the maximum tension stress is particularly important and it is unclear which process – injection molding or dice-and-fill – is better from the standpoint of tension failure. Unless the molded ceramic can be fired under pressure, it is likely that there will be numerous surface defects. Whether the surface is better or worse when diced is an open question. This is one of the issues that can be resolved through careful cycles-to-failure testing (i.e., generation of S-N curves).

Lateral Modes

- Operate in the conduction band so that filler moves in phase with ceramic for direct-radiating 1-3 structures
- Operate in the stop band if using rods as individual array elements to reduce cross-talk
- Internal damping only reduces lateral modes if the lateral extent is sufficiently large
- Lower sound speed of lateral modes puts spurious modes well below band of interest for high-frequency direct radiating structures
- Lower sound speed of lateral modes can put spurious modes *in the band of interest* for transducers that use 1-3 as active layer in mass-loaded resonant system
- Lower sound speed of lateral modes can introduce spurious angular response in hydrophone elements
- More complete specifications should be made available for 1-3 composites: lateral sound speeds for compressional and shear modes, dispersion relations.

Another advertised attribute of 1-3 composites is the suppression of lateral modes. There are two types of "suppression." If the lateral extent of the material is sufficiently large and the damping sufficiently great, then lateral modes are heavily damped. Even if they are near the frequency band of interest, their affect on performance may be small.

There are several factors that determine the nature of wave propagation in the plane of a layer of 1-3 material. The material is a two-dimensionally periodic structure (a pattern of ceramic and filler) and this periodicity affects propagation significantly. For either lateral compressional waves or lateral shear waves, the phase speed is a function of frequency and for some ranges of frequencies propagation turns to exponential decay ("stop bands"). For frequencies at which the ceramic and filler move more or less together ("low frequencies"), effective properties can be determined for the material and a homogeneous-layer model based on those effective properties is reasonably accurate. As the frequency increases the phase and amplitude relationship between ceramic motion and filler motion changes until adjacent ceramic elements are moving in opposition. This marks the upper end of the lower "conduction" band. In a lossless, infinite material, for some range of frequencies above this conduction band, there are no propagating waves, just exponential decay away from the drive point. This is the first "stop" band. Above this stop band, propagating waves are again possible but now the ceramic and filler move 180-degrees out of phase.

Depending on the structure of the material and the wave properties of the ceramic and filler, this conduction/stop structure can be complicated but the fact that it exists can be exploited in designs as long as the lateral extent of the material is large compared to the ceramic-element spacing. For example, if the filler must move in phase with the ceramic as in an uncapped transducer, then the material must be operated in the lower conduction band (and the effective properties may be adequate to model the performance). If a piece of 1-3 material is used as the base material for an array in which individual ceramic elements are used as the array elements, then the material should be operated in the stop band to reduce crosstalk between elements.

Unfortunately, many producers of 1-3 material, either injection molded or dice-and-fill, do not provide the dispersion relationships for the material. (This is in contrast to much of the foundational literature regarding 1-3 composites. Much of this early work focused specifically on the dispersion relationships for wave propagation in periodic material.) It is, however, difficult to measure the dispersion relationship accurately with a sample that is not large in lateral extent. Perhaps this difficulty is an indication that the infinite-extent dispersion characteristics are not particularly useful for the sizes of 1-3 material typically used in practical transducers.

Often pieces of 1-3 composite are used in transducers but the lateral extent is not large with respect to the ceramic-element spacing. If the damping introduced by the filler is sufficiently large then lateral modes are inhibited. However, when 1-3 material is used in a mass-loaded structure, the lateral extent is often insufficient to allow the filler damping to suppress lateral modes. Since the effective lateral sound speed is substantially smaller than the effective sound speed in the direction of the ceramic elements, lateral resonances can be problematic whereas they would not be for a piece of solid ceramic. In this circumstance, 1-3 material is worse than solid ceramic or diced/unfilled material with respect to lateral modes. Again, it is critical to specify the application and the relevant material properties when asserting advantages for a particular material or configuration.

The effect of lateral resonances depends on configuration. In the mass-loaded structure (like a tonpilz), the thickness of the material is a small fraction of a wavelength. A smaller effective sound speed laterally can then lead to lateral resonances close to the intended transducer resonance even though the material dimension is significantly larger laterally. Since this configuration constrains the surface motion (via the head and tail caps), the wave motion most likely to interfere with intended operation is lateral compressional wave motion.

On the other hand, if the 1-3 material is not so constrained at its faces, then lateral shear modes may also be important from the standpoint of parasitic resonances. If the material is not mass loaded, however, and it is much smaller in the thickness dimension than in any lateral dimension, the lateral sound speed would have to be much lower than the longitudinal sound speed for parasitic resonances to be important. In practice, parasitic resonances are more troublesome with mass-loaded transducer structures than, say, the high-frequency medical transducers that may be "loaded" only with several matching layers.

This is not to say that unloaded 1-3 material is free from parasitic resonance problems. If the material is used as an isolated hydrophone element with the intent of exploiting the substantially better hydrostatic performance than solid ceramic, great care must be exercised to prevent spurious *angular* response. For acoustic waves arriving away from the normal direction (the 3-direction of the 1-3 ceramic rods), lateral shear and compressional waves can be generated in the material. This can lead to phase cancellation between the incident pressure field on the surface and the laterally propagated wave inside the material. The internal propagation speed may be such that for some angles the lateral wave inside the composite cancels the response to the external field and produces a spurious null in the directionality. This is especially true for excitation of lateral shear waves in the material for two reasons: (1) the shear-wave speeds can easily be well below that of the sound speed in the water, and (2) shear waves are more easily excited than lateral compressional waves for off-normal incidence waves in the water. (Compressional waves would become important as the angle of incidence approached 90 degrees from the ceramic 3-direction.)

Self Heating

- Filler limits maximum operating temperature of 1-3 material to temperatures far below the Curie temperature of the ceramic
- High-thermal-conductivity filler may reduce temperature rise at high drive levels but not loss in efficiency resulting from high loss tangent
- Loss tangent increases with increasing electric field – sharply in PZT5H
- Loss tangent increases with increasing temperature leading to possibility of thermal runaway

One clear problem with 1-3 materials is temperature tolerance of the filler. Typically the ceramic can operate at considerably higher temperatures than the filler material so thermal management becomes a critical design issue. Even for fillers with relatively high thermal conductivity, the temperature at the ceramic/filler bond surfaces can be sufficiently high to destroy the integrity of that bond. Furthermore, power transducers tend to operate more effectively with high ceramic volume fractions and high coupling factors argue for large height-to-width aspect ratios. Both of these attributes lead to high thermal resistance from the center of the fill material out to the surfaces.

It should, however, be emphasized that providing a suitable path to conduct heat out of the 1-3 material may solve the problem of excessive temperature in the filler but it does not remove the problems associated with the heat generation *mechanism*. For example, the loss tangent in PZT5H is a strong function of drive level (e.g., applied electric field) and can exceed 10 percent at high drive levels. In a transducer using PZT5H-based composite, thermal design would be critical. But, even if the filler temperature can be controlled, this high loss tangent still represents a substantial reduction in achievable efficiency. Furthermore, providing an effective path for heat transfer also does not change the much lower coercive field of PZT5H compared to PZT4 or PZT8.

Sometimes maximum power density is given as a thermal limit for a material but, in the case of 1-3 composites, one limiting aspect of high-power operation is the temperature of the filler. The relationship between power density and filler temperature depends on the environment of the material – the thermal conductivities and dimensions of the various components – and the components' connection to thermal reservoirs.

Bandwidth

- Larger coupling factor in 1-3 material leads to larger bandwidth in some circumstances
- Higher loss leads to larger bandwidth in some circumstances at the expense of efficiency and maximum power
- Closer impedance match to water in 1-3 material leads to larger bandwidth in transducer elements without matching layers
- Bandwidth must be understood in the context of the transducer structure and intended application
- If phase response is important (as for broadband pulse applications), then "increasing" bandwidth with multiple-resonance structures is counterproductive.

Another of the advertised advantages of 1-3 material is large bandwidth. Unfortunately, there is no uniformity in definition of bandwidth. As for other issues, the configuration of the transducer and the ultimate application determine the appropriate definition of bandwidth. In some applications, 1-3 material will provide a larger bandwidth than solid ceramic but the associated cost (in terms of power output, or efficiency, for example) must also be assessed.

To put the issue of bandwidth in perspective, consider the following definitions of transducer bandwidth:

a. The 3-dB down points on the transmitting voltage response (TVR) function.

b. The resonance frequency divided by the quality factor, Q, of the transducer.

c. The 3-dB down points on the transmit/receive insertion loss function.

d. The region of frequency over which the ratio of volt-amperes drive to acoustic power output is less than 10.

e. The range of frequency over which the transmit (or receive) phase response is linear within 10 percent.

(In each case, the specific numbers can be argued. Here, we are only considering applicability and consequence.)

While each of the above definitions can be considered a legitimate descriptor of transducer bandwidth, each measure is applicable to certain circumstances. We must distinguish between high-Q and low-Q transducers. We must distinguish between transducers intended for narrowband signals that might appear at many different frequencies compared to transducers intended for broadband signals. We must distinguish between applications in which there are no volume, weight, or efficiency requirements on the drive amplifier and those applications in which the drive amplifier is constrained.

Indirect measures must always be used with caution. For example, coupling factor has a direct relationship to the separation between the resonance and anti-resonance frequencies but this separation does not always have a direct relationship to bandwidth. In many systems, loss is the dominant factor in determining bandwidth and the coupling factor does not include losses.

(One can, in theory, shape the spectrum of the drive signal to "flatten" the TVR at the expense of reduced power at the TVR peak frequency. However, in practice, this may result in a load on the power amplifier that it so highly reactive it is not practical to run such an inverse-matched transducer at moderate or high power.)

Consider each of the definitions in further detail:

a. *The 3-dB down points on the transmitting voltage response (TVR) function*. In the simple transducer model, the TVR amplitude rises as frequency-squared to a peak near the peak in admittance. Beyond this peak, the TVR levels out then drops slowly with increasing frequency. If the transducer is lightly damped, the 3-dB (or 6-dB) points may be local to the resonance peak. The bandwidth by this definition would be controlled by loss (either internal or radiation loss), not by coupling factor. If the Q is sufficiently low that the resonance peak is less than 3 dB above the higher frequency "plateau," then the bandwidth may be significantly larger than suggested by the losses (though still not accurately determined by the coupling factor).

b. *The resonance frequency divided by the quality factor, Q, of the transducer*. (We will not consider the circular definition here in which the Q is determined from the measured 3-dB down points in the TVR. In that case, this definition is identical to the first one.) If the water-loaded Q of the transducer is greater than 10 (or so), this definition is reasonable for many applications as long as secondary resonances are far enough away from the principal resonance (at least a few Q-determined bandwidths away). This is not a good measure for multiply resonant transducers or for well-damped transducers (*e.g.*, the bandwidth of a loudspeaker is far higher than suggested by the Q of its fundamental resonance).

c. *The 3-dB down points on the transmit/receive insertion loss function*. If the transducer is intended to be used in both transmit and receive then the overall bandwidth is a composite of the transmit and receive bandwidths. If the transducer is driven by a constant-voltage driver, then the TVR is appropriate for transmit; if the transducer is amplified by a high-impedance voltage amplifier in receive, then the free-field voltage sensitivity (FFVS) is appropriate for receive. The FFVS is nominally flat below resonance with a peak that corresponds in frequency to the dip in the transducer admittance (which is above the peak in the admittance) followed by a roll off in amplitude as the reciprocal of frequency-squared above the resonance peak. Consequently, the aggregate transmit/receive response rises to a peak near the admittance resonance, drops then rises to another peak near the admittance anti-resonance, then drops above that. If the peaks are not too high (i.e., if the transducer damping is not too light) or peaked response at either end of the "passband" is not troublesome, then the bandwidth is related to the coupling factor, which describes the separation of the resonance and anti-resonance of the admittance. Notice, also, that if a constant-current amplifier drove the transducer, the transmitting current response (TCR) would be the appropriate transmit measure and the peak in the TCR occurs at the admittance anti-resonance. A transmit/receive system designed for a constant-current drive would not achieve the bandwidth implied by the coupling factor since the TCR and FFVS peaks occur at nearly the same frequency.

d. *The region of frequency over which the ratio of volt-amperes drive to acoustic power output is less than 10.* It is relatively easy to produce a transducer that's difficult to drive with practical power amplifiers. If the load is highly reactive, then very large voltages may be required even though the active element would not see those large voltages. Reactive tuning elements are used effectively for narrowband transducers but such strategies are limited in their effectiveness for broadband transducers. This measure of bandwidth is the reciprocal of the product of electrical-load power factor and efficiency and is the only measure discussed here that considers the problem of power-amplifier compatibility with the transducer. Other measures of bandwidth give higher bandwidth with higher internal damping but, in this measure, if the efficiency drops, the ratio of volt-amperes to acoustic power rises, which reduces the bandwidth measure. This can be a challenging quantity to measure since it requires an accurate assessment of acoustic power output rather than pressure on the main beam.

e. *The range of frequency over which the transmit (or receive, or transmit/receive) phase response is linear within 10 percent.* One of the most neglected features of transducer design is the phase response. For some applications, flatness of the magnitude of the frequency response is important but pulse shape and broadband system response are affected strongly by the phase of any element in the system. If a transducer is intended for true broadband operation using coherent processing of designer pulses, then the phase response can be critical. If the phase of a transducer is not linear with frequency over the spectral content of an input pulse, the transmitted pulse will be distorted. In systems that depend on coherent processing (matched-filter, for example), this distortion represents an additional processing loss. This is a particular weakness of the multiple-resonance transducer design. The multiple-resonance design seeks to produce a relatively flat magnitude response by arranging a number of resonances in close proximity. While this can produce a more-or-less uniform magnitude response over a broader band than any individual resonance, rapid phase changes are typically introduced and the range of linear phase can actually be smaller than for any of the isolated resonances. In principle, an accurate calibration in both magnitude and phase could be used to compensate but then the resonance frequencies would have to be sufficiently stable to ensure that the locations (in frequency) of the rapid phase changes are accurately represented by the calibration. Normally, the resonance frequencies shift slightly with depth and temperature. This does not have a large impact on the magnitude response or on the overall shape of the phase response but the regions of rapid phase change shift and compensation by a fixed calibration function would introduce even more phase problems.

This is not a complete list of bandwidth definitions. For example, the bandwidth could be defined in terms of the transmitting power response or in terms of the efficiency as a function of frequency. *It is important to select a measure of bandwidth that is relevant to the intended application of the transducer*, though, rather than the definition that makes the material or the design look the best on paper.

Where then does 1-3 material fit in with regard to bandwidth design? When the higher coupling factor can actually be achieved in practice, those bandwidth definitions that are directly related to coupling factor would benefit. The increased bandwidth of a transducer using 1-3 material may be the result of the higher damping, though, and in that case the efficiency and maximum power output suffer. The fill material increases the mechanical damping (and dielectric loss) of the transducer system and it may be that the increased internal damping is of more consequence with regard to system bandwidth than the improvement in coupling factor.

If PZT5H is used in a 1-3 composite (compared to PZT4 or PZT8), then the potential for coupling-factor improvement over solid material is greater (the composite structure has more potential for coupling-factor improvement the greater the difference between the ceramic's planar coupling factor and the 33 coupling factor). However, for high-drive applications, the far higher loss tangent in PZT5H probably overwhelms the coupling factor improvement and the bandwidth "improvement" may be dominated by internal loss.

Certainly one aspect of improved bandwidth that can be exploited with 1-3 materials (and is a key aspect of their advantage in high-frequency medical ultrasound applications) is the impedance match to the water. Better impedance match to water produces wider bandwidth (from both response flatness and phase linearity points of view) but, unlike increased internal loss, without a corresponding penalty in efficiency. A bare 1-3 disk would be expected to have significantly higher bandwidth than a bare solid disk. Because moderate and low frequency applications use head-mass loading to reduce the natural resonance frequency, impedance matching is not relevant in those cases. Also, it is an open question whether or not a solid disk with matching layers has a smaller potential bandwidth than a 1-3 disk with matching layers. Certainly, the matching layer structure may be less complicated for the 1-3 system since the intrinsic impedance of the 1-3 material is closer to that of water. Notice also that, as the ceramic volume fraction increases in the 1-3 material, the impedance mismatch worsens.

Stress and Failure

- Mechanical prestress is generally impractical for direct-radiating 1-3 elements
- Buckling failure of rods must be considered in design of prestressed tonpilz-like structures
- Failure measurements of materials should include cycles to failure and high-cycle, reduced stress tests

There are at least two important aspects of mechanical failure that are relevant to 1-3 composites. Here again, a critical distinction involves the transducer configuration or structure. If the structure permits application of a prestress then considerably higher dynamic stress is permissible. The mass-compliance structure (like the tonpilz) can often be designed with a prestress bolt whereas the "unloaded" structure in which the 1-3 material is used in thickness resonance is normally impractical to prestress. Consequently, the 1-3 material in thickness-resonance mode may experience tension failure (at the midpoint of the ceramic rods if the resonance is half-wavelength) at high drive levels.

With respect to prestress, solid ceramic has a distinct advantage over a matrix of relatively high-aspect-ratio rods. Rods under compression are susceptible to spalling near the ends or buckling and this may limit the level of prestress (and dynamic compressive stress) that can be achieved in a high-reliability design. This is one of the few instances in which the filler may provide a performance improvement in a mass-loaded (capped) configuration. The filler will delay the onset of buckling depending on the ceramic volume fraction and the properties of the fill material.

The second aspect is stress-concentration-induced failure. Although I am not aware of any studies that address this issue in 1-3 composites, surface flaws can precipitate premature failure in brittle materials under dynamic loading. Since material properties are more variable with injection-molded material than dice-and-fill, it is natural to suspect a higher incidence of voids or flaws in injection-molded material and this may cause these materials to fail sooner under high-cycle conditions. It should not, however, be assumed that dice-and-fill would be free of such problems.

Although classical brittle materials have very steep S-N curves (curves of failure stress as a function of number of cycles of load), it is still dangerous to characterize stress-related failure by low-cycle testing. A material often will fail at a considerably lower stress if that stress is applied for many cycles than if the stress is increased rapidly in a simple failure test. S-N curves should be developed for failure characterization of materials as it is a means of understanding the source of failure.

Unipolar Drive

- Unipolar drive should extend the permissible electric field limits for PZT5H
- Unipolar drive may reduce the rise in loss tangent with increased field
- The cost of unipolar drive must be considered in terms of overall system efficiency and size (including the power amplifier and associated drive components)

One of the critical problems associated with the use of PZT5H in 1-3 composites is the low coercive field and the associated high dielectric loss at high drive levels. This suggests investigation of unipolar drive. Although unipolar drive is common practice in piezoelectric actuators, there exists only limited experience with sonar transducers. By avoiding application of the electric field in the direction opposite to the internal polarization, depoling and the excess loss associated with approaching and exceeding the coercive field can, in principle, be reduced. Reported results with unipolar drive of conventional transducers generally omit the details of power-amplifier efficiency and size and this may be an important drawback to unipolar drive. However, given the limited potential for PZT5H in 1-3 composites, some experimentation with unipolar drive is probably warranted. If the loss tangent rise with drive field can be controlled and higher absolute fields can be attained without sacrificing reliability, then materials made from PZT5H may start to approach the performance achievable with harder ceramics.

Importance of Reporting Results Completely

One of the most challenging aspects of sorting through literature and presentations on 1-3 composites is understanding the basis of quoted results. (See the extended discussion of bandwidth above.) Results presented without sufficient supporting information are often of little value for transducer design even if those results seem to indicate substantial advances in technology.

For example, efficiency is an ambiguous measure if not fully described. In a battery-operated system, or a system in which the power amplifier is space-constrained, the efficiency that relates the acoustic power output to the electrical power input to the transducer terminals describes only part of the system. For such systems, a transducer with a challenging load factor (with large and variable reactance) can have a high terminals-to-acoustics efficiency but might require a low-efficiency (or low power-density) amplifier for broadband operation.

Furthermore, efficiency and power should always be presented together. Quoting an efficiency number and a power output when each figure was taken at a different operating point is a misrepresentation of performance. Curves of both efficiency and power should be presented as functions of operating condition so that system designs can be done with confidence. High efficiency at low power may be irrelevant; efficiency measured at low drive levels cannot be expected to be representative of efficiency at high drive levels particularly if a soft ceramic is used. The dependence of efficiency on frequency should be carefully reported. An efficiency that drops rapidly away from some optimum frequency may result in inordinate demands on power amplifiers for broadband operation.

Coupling factor is also such a common performance measure that it is often reported inadequately. It is certainly a useful measure as long as the underlying assumptions are respected but there is little excuse for not reporting the applicable conditions. Is the coupling factor the low-frequency theoretical value for the material; is it a value measured for the material; is it measured for the transducer; if the measurement is based on measured admittance peak and null frequencies, has it been corrected?

(Although I have not done an exhaustive literature search, I am not aware of any foundational text that defines coupling factor as κ rather than κ^2. With the same caveat, I am also not aware of any important transducer relationship that uses κ unless it appears as κ^2. The practice of citing κ for coupling factor is common and creates no problem as long as it is clearly stated but the practice is still questionable. Because coupling factor ranges from zero to one, taking the square root gives a larger value, which makes the system seem "better." If this is uniformly done for all transducers, there is no advantage gained; however, performance generally depends on κ^2 rather then κ. While it might seem that the square root is appropriate given that the coupling factor is defined in terms of energy ratios, it appears as κ^2 in equations that relate *amplitudes*.)

Other performance measures such as TVR and TCR must be reported along with the applicable conditions. If these values are measured at low drive level, they may not be representative of the performance achievable under operational conditions. In radio-frequency amplifier evaluation and development it is common practice to measure and report output power as a function of input power from noise floor to some specified level of "nonlinearity" such as 1-dB compression point or third-order intercept. A similar characterization would be useful for acoustic power transducers as well although the point of transducer failure would have to be considered as well.

For systems with volume constraint (i.e., most systems), total system power density and energy density can be critical measures. Here, the power density or energy density of the transducer material is only one factor and, while the material limits can limit the overall design, the material limits may not be achievable in a practical system.

All of these concerns share a common aspect: single, isolated measures are generally misleading for transducer engineering. Although it is much easier to "design" a transducer using a single measure, this process rarely leads to good designs and often inhibits innovation. It should also be kept in mind that the customer rarely (never?) wants a transducer with a high coupling factor, or a high d coefficient, or a high $g_h d_h$ product. The customer wants a transducer to meet a particular operational specification. The transducer designer may use intermediate measures to guide the design but must never mistake the intermediate measures for the ultimate performance goals.

Additional References (also see Report 1)

K. G. Eyster, Comparison of thermal and electric field test data for piezoelectric ceramic materials PZT8, PZT5J, PZT5H and piezoelectric composite material MSI53HD" Naval Undersea Warfare Center Division, Newport Technical Memorandum 00-150, 20 December 2000.

C. G. Oakley, "Analysis and development of piezoelectric composites for medical ultrasound transducer applications," Ph.D. Thesis, The Pennsylvania State University, May 1991.

A. L. Butler and J. L. Butler, "1-3 piezocomposite sandwich transducer array performance," Final Report CDRL A001, Image Acoustics, 3 June 2003.

Presentation slides from 1-3 Composite Transmitter Meeting, Naval Research Lab, 16 January 1998.

D. J. Van Tol, "1-3 composite high voltage tests," personal communication, 12 September 1997.

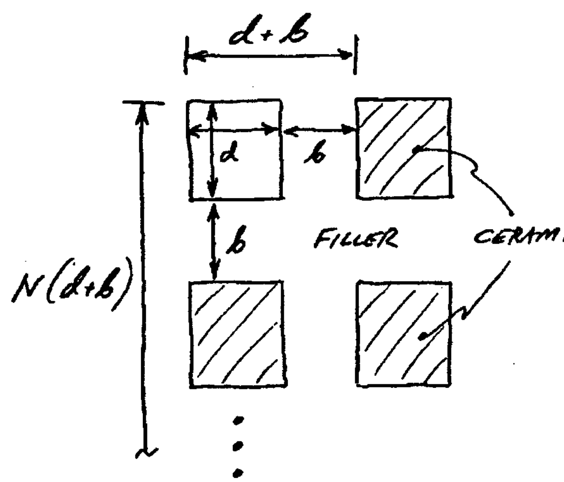
Reference Material

The material included in the following appendix sections is intended merely to support several of the statements in the text. For example, many authors have addressed calculation of equivalent properties in 1-3 composites. Appendix A is included not for any claim to originality; it is included to provide a quantitative basis for the discussion of the impact of lateral modes on the performance of 1-3 material in mass-loaded ("capped") transducer elements. Appendix B and Appendix C are included for convenience. This material is available elsewhere.

Appendix A: Effective Lateral Sound Speed

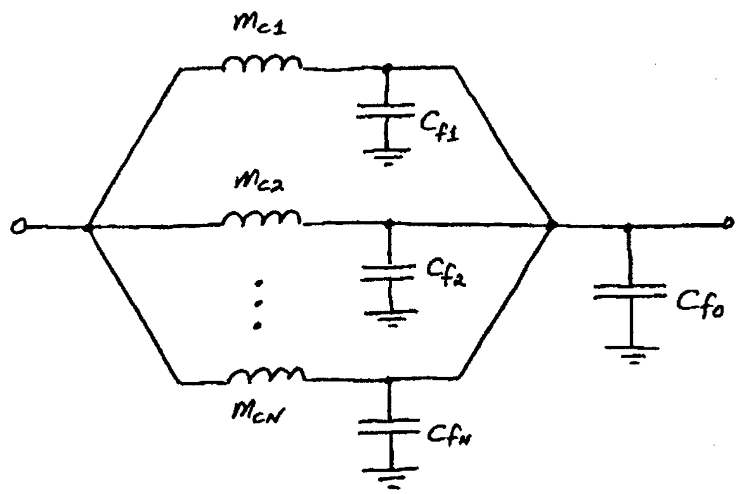
What follows is an approximation for the effective lateral sound speed in a 1-3 composite. The derivation considers a compressional wave that propagates in a direction perpendicular to the 3-direction of the piezoelectric elements and in the direction of the rows of piezoelectric elements. A similar model could be developed for shear waves but the compressional wave may be more important when the 1-3 material is sandwiched between stiffer end masses (the situation in which the lateral resonances are most troublesome). Note that this effective sound speed is a low-frequency approximation; it is, in effect, the slope of the dispersion curve in the lowest conduction band and should be a reasonable approximation for at least the lower half of that band.

Consider the arrangement of square-cross-section piezoelectric elements shown below.



The arrangement is square in the two dimensions perpendicular to the 3-direction in the piezoelectric material (out of the page, here). There are N ceramic elements across the width of the material; the ceramic elements have square cross-section with dimension, d, and have thickness (i.e., length in the 3-direction), t. The distance through the filler from element to element is b. We will consider a plane compressional wave coming from the left through the material toward the right. (The compressional speed may be somewhat different for directions other than along a row (or column) but we are only intending to approximate the speed for the purposes of outlining the possibility of spurious mode generation.)

To approximate the effective compressional speed, we will use a fluid-acoustic analogy in which the variables are pressure and volume velocity. Volume velocity is particle velocity times cross-sectional area and volume velocity is conserved in an acoustic "flow" through a structure with varying area of passage. We will consider that the ceramic material dominates the inertial effects and that the filler dominates the compressibility effects. Therefore, the 1-3 structure appears, acoustically, to be a matrix of mass elements surrounded by a network of compliant passages. An equivalent circuit representation for one column of the 1-3 structure is shown below.



If we consider the start of the column the leading edge of the N ceramic elements, there would be N parallel branches that describe the mass of the ceramic elements and the compliance of the filler between those elements. This is followed by the compliance of the section of filler between this column of ceramic elements and the next column of elements.

It is vital to express these elements properly. Their impedances must be equivalent to ratios of pressure to volume velocity rather than pressure to particle velocity or force to particle velocity. Consequently, acoustic masses are physical masses divided by the square of the cross-sectional area and acoustic compliances are the physical volumes divided by the elastic modulus. Therefore,

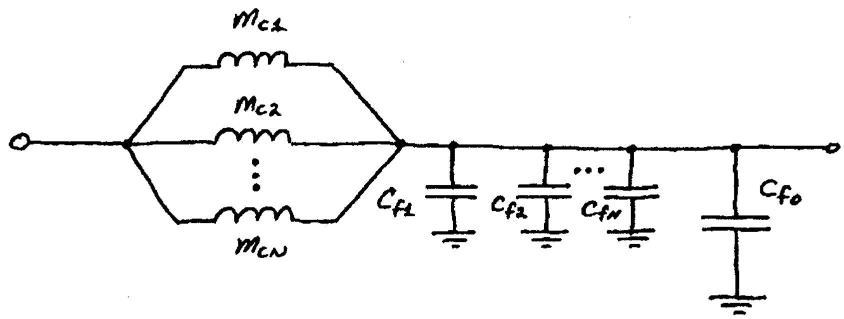
$$m_{ci} = \frac{\rho_{cer} V}{A^2} = \frac{\rho_{cer}\, d^2\, t}{(d\,t)^2} = \frac{\rho_{cer}}{t} \quad ; \quad i = 1, N$$

$$C_{fi} = \frac{V}{E_{fill}} = \frac{b\,d\,t}{E_{fill}} \quad ; \quad i = 1, N$$

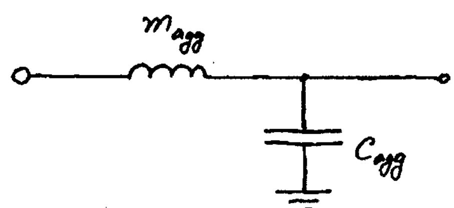
and

$$C_{f0} = \frac{N(d+b)bt}{E_{fill}}$$

The equivalent circuit can also be re-arranged to illustrate how quantities can be combined:



An entire column can then be represented by a single aggregate mass and aggregate compliance,



where

$$m_{agg} = \frac{m_{ci}}{N} = \frac{\rho_{cer}}{Nt}$$

and

$$C_{agg} = C_{f0} + NC_{fi} = \frac{Nb^2t(1 + 2d/b)}{E_{fill}}$$

A series connection of simple mass-compliance networks (one of which is shown above) approximates a transmission line and the fundamental properties of that transmission line can be expressed in terms of the mass per unit length,

$$\tilde{m}_{agg} = \frac{m_{agg}}{b + d} = \frac{\rho_{cer}}{Nbt(1 + d/b)}$$

and the compliance per unit length,

$$\tilde{C}_{agg} = \frac{N b t (1 + 2d/b)}{E_{fill}(1 + d/b)}$$

The speed of propagation in the transmission line model is the square root of the reciprocal of the product of mass per unit length and compliance per unit length. Calling this speed the speed of transverse compressional waves, v_{tr},

$$v_{tr} = \sqrt{\frac{1}{\tilde{m}_{agg}\,\tilde{C}_{agg}}} = \sqrt{\frac{E_{fill}}{\rho_{cer}}\frac{(1 + d/b)^2}{(1 + 2d/b)}}$$

Generally, it is more convenient to express this result in terms of the ceramic volume fraction, vf, of the 1-3 material:

$$vf = \frac{V_{cer}}{V_{total}} = \frac{N d^2 t}{N(b + d)^2} = \frac{1}{(1 + b/d)^2}$$

Solving for the ratio of d to b gives

$$d/b = \frac{\sqrt{vf}}{1 - \sqrt{vf}}$$

This permits expressing the propagation speed as

$$v_{tr} = \sqrt{\frac{E_{fill}}{\rho_{cer}}\frac{1}{1 - vf}}$$

It is also useful to write the ratio of this transverse speed of propagation to the 33 bar speed in the ceramic,

$$\frac{v_{tr}}{v_{33}} = \sqrt{\frac{\rho_{cer}}{E_{33}}}\sqrt{\frac{E_{fill}}{\rho_{cer}}\frac{1}{1 - vf}} = \sqrt{\frac{E_{fill}}{E_{33}}}\sqrt{\frac{1}{1 - vf}}$$

(We could also have used as reference speed the propagation speed of compressional waves in the 3-direction through the composite but this complication has been avoided here since the relationship between the ceramic speed and the composite speed has already been determined in the first report.)

Bear in mind the central approximations – the inertial effects are controlled by the mass of the ceramic elements and the compressibility is controlled by the compressibility of the filler. The expression above is not valid in either the zero or unity limit of ceramic volume fraction because these assumptions are not at all accurate at either limit. For the range of volume fraction typical of power transducer material, though, the assumptions are reasonable.

As an example, consider a 1-3 material made from PZT4 with a filler of Stycast 2057. The density of the filler is 1590 kg/m^3 and the density of PZT4 is 7600 kg/m^3 so for reasonable volume fractions the mass is dominated by the PZT4 (though this is the weaker of the two assumptions). For the ceramic modulus, we consider the bar stiffness with $D_3 = 0$ since the electrodes are on the 3-faces:

$$E_{33} = \frac{1}{s_{33}^D} = 121 \times 10^9 \ N/m^2$$

For the filler modulus, we consider the stiffness under the conditions that strains are allowed in both transverse directions but not in the thickness direction (the 3-direction of the ceramic elements). Since we have the stiffness coefficients for isotropic Stycast 2057 – $c_{11} = 12.5 \times 10^9$ N/m^2 and $c_{12} = 5.7 \times 10^9$ N/m^2 – we can write the relationships between stress and strain assuming that the stress is applied only in one of the transverse dimensions:

$$\begin{aligned} T_1 &= c_{11} S_1 + c_{12} S_2 \\ 0 &= c_{12} S_1 + c_{11} S_2 \end{aligned}$$

Solving for T_1/S_1 gives the effective modulus of the filler:

$$E_{fill} = \frac{T_1}{S_1} = c_{11}\left[1 - \left(c_{12}/c_{11}\right)^2\right] = 9.9 \times 10^9 \ N/m^2$$

Using these values for filler and ceramic modulii and a composite with a volume fraction of one-quarter, the ratio of transverse compressional waves to bar speed is 0.33. If the volume fraction were one-half, the ratio of speeds would be 0.4.

Appendix B: Volt-Amperes per Acoustic Watt

The performance measure, the ratio of volt-amperes electrical to acoustic power radiated, is a composite of transducer electroacoustic efficiency and electrical power factor. If e and i are the complex voltage and current amplitudes at the transducer's electrical terminals, then VA, the volt-amperes electrical, is

$$VA = \frac{1}{2}|e||i|$$

The input electrical power is related to this product and the phase between current and voltage:

$$\mathbf{P}_{electrical} = \frac{1}{2}\mathrm{Re}\left[e^{*} i\right] = \frac{1}{2}|e||i|\cos\phi$$

where ϕ is the phase angle between current and voltage (and $\cos\phi$ is the power factor). The acoustic output power is the electrical input power times the electroacoustic efficiency,

$$\mathbf{P}_{acs} = \eta \mathbf{P}_{electrical}$$

Therefore, the ratio of volt-amperes to acoustic power is

$$\frac{VA}{\mathbf{P}_{acs}} = \frac{1}{\eta\cos\phi}$$

One viewpoint with regard to this ratio is that, for 100% conversion efficiency and fixed drive current, some drive voltage would be required for a certain acoustic power. For the actual transducer, somewhere in the drive amplifier or matching circuitry there would appear a voltage higher than this drive voltage by the factor, $VA/\mathbf{P}_{acs}$. Besides the difficulty of designing an efficient power amplifier for highly reactive loads, this factor also indicates that electrical breakdown may limit the power of a transducer with a high $VA/\mathbf{P}_{acs}$.

Appendix C: Coupling Factors

For a capped transducer, the low-frequency coupling factor can be used even at resonance since the stress is fairly uniform in the thickness direction in the piezoelectric material. Here, the coupling factors are summarized for three cases:

- 3-3 bar as best-case for 1-3 composite
- disk thickness mode for solid ceramic
- material diced in only one direction

These coupling factors can be calculated easily from the energy expressions,

$$U_{elastic} + U_{mutual} = \frac{1}{2}\sum_{i=1}^{6} S_i T_i$$

and

$$U_{mutual} + U_{dielectric} = \frac{1}{2}\sum_{i=1}^{3} D_i E_i$$

Using these energy densities,

$$\kappa^2 = \frac{U_{mutual}^2}{U_{elastic}\, U_{dielectric}}$$

A. 3-3 Mode Coupling Factor

The relevant assumption here is that the ceramic behaves as a long bar: all stresses are approximately zero except for T_3. Using the equation set, $S(T, E)$ and $D(T, E)$, the coupling factor is

$$\kappa^2 = \frac{d_{33}^2}{s_{33}^E\, \varepsilon_{33}^T}$$

B. Thickness Mode Coupling Factor

In this case, the ceramic behaves as a thin plate so that all of the strains are approximately zero except for S_3. Using the equation set, $T(S, D)$ and $E(S, D)$, the coupling factor is

$$\kappa^2 = \frac{h_{33}^2\, \varepsilon_{33}^S}{c_{33}^D}$$

C. Coupling Factor for Ceramic Diced in One Direction

If a disk of ceramic is diced in one direction only, then the strain in the direction of the cuts is approximately zero while the stress perpendicular to the cuts is approximately zero. The other normal stresses and strains are, in general, nonzero. (The shear stresses and strains are approximately zero, also.) The solution is slightly more involved than either of the previous two cases. The equation for S_3 can be written in terms of T_1, T_3, and E_3. The equation for S_1, which is zero, can be written in terms of T_1, T_3, and E_3 and this equation can be solved for T_1. Substituting this result into the equation for S_3 gives an equation for S_3 in terms of T_3 and E_3. This same result for T_1 can be substituted into the equation for D_3 so that D_3 can be written in terms of T_3 and E_3. Once this is done the energy expressions can be found. The coupling factor is

$$\kappa^2 = \frac{\left[d_{33} - \dfrac{s_{13}^E d_{31}}{s_{11}^E}\right]^2}{\left[s_{33}^E - \dfrac{\left(s_{13}^E\right)^2}{s_{11}^E}\right]\left[\varepsilon_{33}^T - \dfrac{d_{31}^2}{s_{11}^E}\right]}$$

A comparison between the 3-3 and thickness coupling factors is shown in the table below. The improvement in PZT5H is somewhat greater than the improvement in either PZT4 or PZT8.

	κ_{33}^2	κ_{thick}^2	$\kappa_{33}^2/\kappa_{thick}^2$
PZT5H	0.564	0.265	2.13
PZT4	0.468	0.252	1.86
PZT8	0.424	0.228	1.86

The next table shows the effect of dicing in one direction (the "slice" mode). Most of the coupling factor improvement can be obtained by dicing in one direction only.

	κ_{33}^2	κ_{slice}^2	$\kappa_{33}^2/\kappa_{slice}^2$
PZT5H	0.564	0.487	1.16
PZT4	0.468	0.409	1.14
PZT8	0.424	0.368	1.14

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14. ABSTRACT
This report identifieds important practical issues related to 1-3 composites, based on (1) a quantitative comparison between solid ceramic, conventional 1-3 material, and an unfilled bar matrix in the context of transducers employing mass-loading to reduce the resonant frequency and (2) information gathered from researchers experienced in 1-3 composites in both low- and high-frequency applications. Findings include (but are not limited to):
- Transducer configuration is critically importing in determining the applicability of 1-3 composite
- In a transducer in which the active material is sandwiched between mass elements, the filler in a 1-3 composite degrades performance with respect to an unfilled array of piezoelectric rods
- Self heating is only one of several obstacles to the successful use of PZT5H in high-power composites

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